

A global view of aerosols from merged transport models, satellite, and ground observations

Hongqing Liu and R. T. Pinker

Department of Meteorology, University of Maryland, College Park, Maryland, USA

B. N. Holben

Biospheric Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

Received 25 February 2004; revised 6 December 2004; accepted 12 January 2005; published 26 March 2005.

[1] Growing recognition of the importance of natural and anthropogenic aerosols in climate research led to numerous efforts to obtain information on aerosols based on model simulations, satellite remote sensing, and ground observations. This study describes an approach to combine information from independent sources that complement each other in their capabilities to achieve a global characterization of monthly mean clear-sky daytime aerosol optical depth. The following sources of information have been used: simulations from the Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) model; retrievals from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on the Terra satellite; and measurements from the Aerosol Robotic Network (AERONET). Leading empirical orthogonal functions (EOFs) are used to represent the significant variation signals from model and satellite results; the EOFs are fitted to the ground observations to propagate the AERONET information at a global scale. The methodology is implemented with a 2-year time record when collocated data from all three sources are available.

Citation: Liu, H., R. T. Pinker, and B. N. Holben (2005), A global view of aerosols from merged transport models, satellite, and ground observations, *J. Geophys. Res.*, 110, D10S15, doi:10.1029/2004JD004695.

1. Introduction

[2] Natural as well as anthropogenic aerosols affect the global radiation balance directly and indirectly. The direct effects are due to scattering and absorption of radiation with a subsequent influence on the planetary albedo and surface radiative fluxes [Coakley *et al.*, 1983; Charlson *et al.*, 1992; Kiehl and Briegleb, 1993; Boucher and Anderson, 1995; Schwartz, 1996]. Examples of indirect effects are: possible changes of the number and size of cloud droplets [Twomey, 1977; Twomey *et al.*, 1984; Coakley *et al.*, 1987] or effects on precipitation efficiency [Albrecht, 1989]. Reduction in cloud cover caused by solar absorption in haze layers has been considered as a semidirect effect [Hansen *et al.*, 1997; Ackerman *et al.*, 2000]. Aerosols are a major source of uncertainty in estimating radiation budgets, and predicting climate change [Intergovernmental Panel on Climate Change (IPCC), 2002]. Better knowledge of the spatial and temporal variations of aerosol properties is needed, especially of aerosol optical depth (AOD) at standard wavelength (550 nm), which is the most important parameter to characterize extinction of the incoming solar radiation.

[3] Numerous approaches have been developed to study large-scale atmospheric aerosols based on remote sensing and model simulations. Major sensors used for AOD retrievals include the advanced very high resolution radi-

ometer (AVHRR) [Rao *et al.*, 1989; Stowe *et al.*, 1997; Husar *et al.*, 1997; Higurashi and Nakajima, 1999; Mishchenko *et al.*, 1999]; the Total Ozone Mapping Spectrometer (TOMS) [Herman *et al.*, 1997; Torres *et al.*, 1998, 2002]; Polarization and Directionality of the Earth's Reflectance (POLDER) [Goloub *et al.*, 1999; Deuzé *et al.*, 2001]; Moderate resolution Imaging Spectroradiometer (MODIS) [Kaufman *et al.*, 1997; Tanré *et al.*, 1997]; and Multiangle Imaging Spectroradiometer (MISR) [Martonchik *et al.*, 1998]. Detailed descriptions of spaceborne remote sensing of aerosol properties are presented in the work of King *et al.* [1999]. Model simulations of the wide spectrum of aerosol types are provided by chemical transport models (CTMs) that are off-line modules driven by meteorological data or from global circulation models (GCMs) which take aerosol processes as an integrated part within the simulation scheme. Description, intercomparison of models and evaluation against satellite retrievals and ground observations are presented in the work of Penner *et al.* [2002] and Kinne *et al.* [2001, 2003]. Very few historical ground measurements of aerosol properties are available due to limitations of instrument maintenance and calibration, and degradation of the filters used. Recently, a centrally maintained ground-based Aerosol Robotic Network (AERONET) has been in operation for more than 10 years to provide accurate point measurements at more than 100 stations [Holben *et al.*, 1998, 2001].

[4] Each of the above approaches has advantages as well as deficiencies. Ground observations give accurate point

information, yet, are limited in spatial coverage. Satellites have improved geographical coverage, but the accuracy of the retrieved values is affected by surface conditions, cloud contamination, and uncertainties about aerosol microphysical and chemical properties. Models capture the mechanisms of aerosol production, transformation, transport and deposition and provide a comprehensive description of aerosol properties, but the complex processes are simulated with highly parameterized schemes which need continuous evaluation. Integrated analysis is required to combine the useful aspects of the individual data sources to give a complete description [Charlson, 2001; Diner *et al.*, 2004].

[5] Optimal assimilation of AOD on a global scale from multiple data sources requires reliable error information. Obtaining accurate estimates of error variance and covariance structure remains a challenge given the limited “ground truth.” In this work, an empirical method is presented for obtaining representative monthly grid area averaged clear-sky daytime AOD by combining the advantages of each data set. Temporally collocated monthly mean AOD at $0.55\ \mu\text{m}$ from satellite retrievals, model simulations and ground measurements are used. As a major sensor designed to provide high quality, routine retrievals both over ocean and land, MODIS data are selected; GOCART model which produces reasonable spatial structures [Chin *et al.*, 2000] is utilized; the best available ground measurements are taken from the AERONET. Analysis was performed for a 2-year period (March 2000 to February 2002) and spatial domain between 60°S and 60°N where most MODIS retrievals and AERONET stations exist. To obtain a global field, extrapolation to high latitudes has been performed based on the spatial distribution of the GOCART model results.

[6] Data sources used are described in section 2; a quality check of MODIS and AERONET data is presented in section 3; comparison of spatial and temporal variability between GOCART and MODIS data is given in section 4; in section 5 the empirical combination method is introduced and implemented; discussion and summary are presented in section 6.

2. Data Sources

2.1. GOCART Model Simulations

[7] The Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) model is a three-dimensional chemical transport model with a horizontal resolution of 2.5° longitude by 2° latitude and 20–30 vertical layers, depending on the background meteorology used (the Goddard Earth Observing System Data Assimilation System) [Chin *et al.*, 2000, 2002; Ginoux *et al.*, 2001]. As a forward model that provides needed AOD information, GOCART estimates the emissions of the key types of aerosols (sulfate, dust, organic carbon, black carbon and sea salt) and their precursors based on state-of-the-art data sets of fossil/biofuel combustion; biomass burning and surface topographic features. Chemical reactions (e. g., DMS and SO_2 oxidation), transport mechanisms (advection, diffusion and convection), aging and removing processes are built into the model to simulate the aerosol evolution. To derive AOD, dry aerosol mass M_d for each aerosol component is calculated, aerosol optical parameters and hygroscopic effect are assumed to estimate the mass extinction efficiency β , which describes a linear relationship between the dry

aerosol mass and the AOD at specified wavelength. Most of these processes are highly parameterized and could be sources of error. Evaluation of the GOCART AOD against satellite retrievals and AERONET observations revealed that the model has the capability to reproduce prominent spatial and temporal variations, in particular in areas with strong signals (biomass burning and dust dominant) [Chin *et al.*, 2002].

6. Discussion and Summary

[43] When describing the Progressive Retrieval and Assimilation Global Observing Network (PARAGON) concept, Diner *et al.* [2004] emphasize the need to reduce the uncertainties in our understanding of aerosol-climate interactions. Specifically: “The complexity of the aerosol-climate problem implies that no single type of observation or model is sufficient to characterize the current system or to provide the means to predict aerosol impacts in the future with high confidence”. Consequently, information must be drawn from multiple observational and theoretical techniques, platforms, and vantage points, and strategies that explicitly plan for the integration and interpretation of the various components. In the present study an attempt has been made to reduce the errors at global scale in AOD by developing a merging approach to obtain global monthly mean clear-sky daytime AODs, using observations from independent sources. The methodology was implemented with a 2-year record of simultaneous information from model outputs, satellite retrievals and ground observations. This approach has the following merits:

[44] 1. Leading EOFs can retrieve the significant and geographically continuous variation signals from model and satellite data.

[45] 2. Fitting the leading EOFs to the ground observations can propagate the AERONET information in an inhomogeneous and anisotropic manner, with an amplitude that is close to the measurements in a general least square sense.

[46] 3. Truncated EOF fitting is robust and not very sensitive to possible sampling errors in the ground observations. If the sampling errors lead to variations that cannot be explained by the leading EOFs, these signals will be largely ignored in the fitting process.

[47] Limitations regarding this scheme are:

[48] 1. It is empirical in nature where assumptions can be only partially tested due to the limited amount of high quality monthly mean, grid area averaged AOD data sets.

[49] 2. Propagation of AERONET information in the time dimension was not implemented. Kaplan *et al.* [1997] constructed a first-order linear Markov model to provide further constraints on the temporal amplitudes. However, a reliable model of this type can be built only when the database of collocated information is expanded.

[50] 3. More realistic observation operator than H might ameliorate the regional representativeness problem of AERONET point measurements. However, finding the relationship between the areal average and point value remains an open issue. It is hoped that the full potential of the proposed approach would be achieved when longer term information from independent sources becomes available in the future.